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HEAVY QUARKONIA SPECTROSCOPY AND DECAYS

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ABSTRACT

The experimental status of stable bound states made out of heavy quarks is reviewed. The need for a way to deal with the non-perturbative transitions involved calls for precision measurements on one hand, and for discovery of as yet undetected states to confirm predictions on the other. In this article, recent experimental contributions to heavy quarkonia spectroscopy and decay will be reviewed, mostly from data analyzed by the BES and CLEO collaborations.

The most dramatic recent discoveries include the detection of the first stable $L = 2$ state, and a first non-pionic hadronic transition in the Υ system, and a first measurement of $\chi_{cJ} \to \Lambda\bar{\Lambda}$. Scans of the ψ' and $\Upsilon(1, 2, 3S)$ resonances are used to add information on partial and total decay widths.

1 Heavy Quarkonia

Heavy quarkonia are non-relativistic strongly bound quark-antiquark states. Owing to asymptotic freedom, non-relativistic quantum mechanics should hold apply to a good approximation to heavy $Q\bar{Q}$ systems [1]. This allows us to compare heavy quarkonia to another bound particle-antiparticle state with slowly moving constituents, namely positronium. In fact, a similar spectrum of bound states is expected; see Figure 1. The states are characterized by the following quantum numbers: radial excitation n, total spin S, relative orbital momentum L, total spin $\vec{J} = \vec{L} + \vec{S}$, parity P, and C. Not all states have been verified by experiment. Just as positronium, held together electromagnetically, provided a testing ground to gain understanding about that underlying force, studing heavy quarkonia allows us to take a better look at QCD.

The large heavy quark masses result in small values of the running strong coupling constant in annihilation and production processes. In contrast to this, transitions between $Q\bar{Q}$ states, such as radiative de-excitation or splitting off a gluon pair that turns into a pion pair, thereby producing a lower-lying state, are soft processes. Thus many of the processes belong to the regime of non-perturbative QCD, a region that lacks thorough theoretical understanding as of now.

The strong interaction has an impact on many measurements investigating weak physics as well. Also, new physics can turn out to be strongly coupled. This means that any opportunity that presents itself to study aspects of QCD as an example of a strongly coupled theory must be used.

The bound $t\bar{t}$ state is very short lived since it can decay via the weak force, which is not possible for charmonium and bottomonium. This makes it unsuitable for studies of the strong interaction. Also, if the $c\bar{c}/b\bar{b}$ states have masses above open their respective flavor production threshold ($B\bar{B}$ for $b\bar{b}$ states and $D\bar{D}$ states for $c\bar{c}$ systems), they decay fairly quickly. This leaves eight quasi-stable states in charmonium and thirty in bottomonium for spectroscopy studies.

1.1 Theoretical Understanding

As mentioned above, heavy onia spectroscopy highlights the soft regime of QCD, making it impossible to use perturbative methods to calculate transition quantities. Perturbation theory does describe the long distance part of the heavy quark potential.

This puts emphasis on the need for calculation methods that can handle non-perturbative phenomena such as Lattice QCD. Recent developments allow to overcome the previous limitations that prevented unquenched calculations, *i.e.* that did not treat light quark loops, a neglect that was estimated to easily contribute uncertainties at the 10% level. As these become available, it is essential that their results be subject to critical comparison with experiment in order to enhance confidence before employing the methods to other areas such as the weak sector of heavy quark physics.

Another solution is to use the quark velocity and α_s as expansion parameters, opening the way for effective theories of the strong interaction.

Yet another approach is the use of phenomenological models, the parameters of which must be determined from experimental data. A common ansatz is a potential consisting of a Coulomb like term $\sim 1/r$, where r is the distance between the quarks, and a confinement term, linear in r.

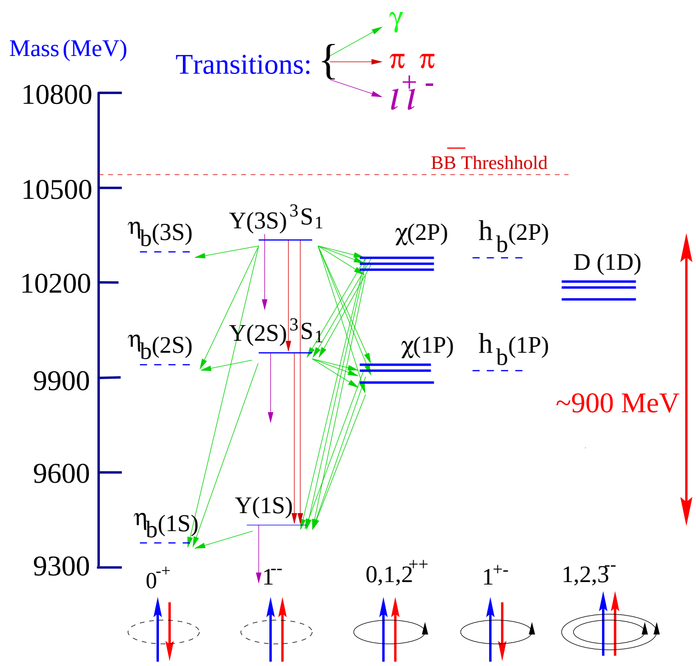

Figure 1: *The spectrum of stable $b\bar{b}$ states and allowed transitions within the system. Parallel arrows at the bottom stand for a symmetric configuation, producing a state of total spin $S = 1$, antiparallel arrows for an antisymmetric one ($S = 0$). Also indicated is the orbital momentum, increasing from left to right. A similar spectrum exists for charmonium. The states are labelled similarly, albeit with a subscript c instead of b, and the $^{2S+1}L_J = ^3S_1$ states are called ψ (J/ψ for $n = 1$).*

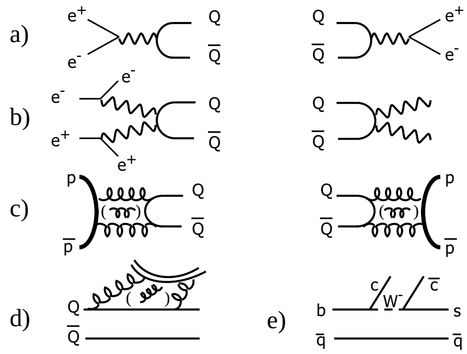

Figure 2: *Heavy quarkonia production diagrams.*
Production (left) and their corresponding decay (right) processes:
a) $e^+e^- \rightarrow \gamma^* \rightarrow Q\bar{Q}$*, b)* $\gamma\gamma \rightarrow Q\bar{Q}$*, c)* $p\bar{p} \rightarrow$ *gluons* $\rightarrow Q\bar{Q}$*.*
d) Quarkonium de-excitation by emission of two pions, e) creating charmonium from a B *meson.*

2 Production

Quarkonia can be produced in several ways, which reach different states within the spectrum. The first three listed here are mere reversals of $Q\bar{Q}$ decay processes and are sketched in Figure 2a), b), and c).

In electron positron colliders, the reaction $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$ results in states that can couple to a virtual photon, namely n^3S_1 such as J/ψ and Υ with a tiny admixture of n^3D_1. Direct resonance production offers the advantage of large production rates, giving access to branching fractions even as small as 10^{-5}.

Two-photon collisions allow direct creation of $J = 0, 2$ states, *e.g.* $\eta_{[c,b]}$, $\chi_{[c,b][0,2]}$. While they are readily available at e^+e^- machines, they suffer from small production rates. Still they provide an important contribution in that they can be used for discovery purposes.

Hadron machines, being able to produce any onia state in principle by annihilation of the $p\bar{p}$ pair into gluons, continue to contribute mostly to the study of production of charmonia. This environment suffers from large background; thereby one has to focus on exclusive decays.

Two more scenarios: Downward transitions within the system provide an important route to otherwise not reachable states. Any collider that can produce B mesons, be it a hadron accelerator or an e^+e^- machine running on the $\Upsilon(4S)$ resonance, has access to $c\bar{c}$ states through weak decays of the b quark. These two processes are sketched in Figure 2 d) and e).

An important background for the reaction $e^+e^- \rightarrow Q\bar{Q} \rightarrow X$, or more explicitly, $e^+e^- \rightarrow \gamma^* \rightarrow Q\bar{Q} \rightarrow \gamma^* \rightarrow X$, is the case in which no intermediate

$Q\bar{Q}$ resonance is formed. The presence of this channel adds to the measured cross-section both directly and by interference, which can be a sizeable contribution [2]. In most measurements, this contribution is not taken into account or subtracted. This background needs to be either measured, by running off the relevant resonance, or calculated. In measurements of the cross-section as function of energy (scans), the non-resonant production can be explicitly taken into account when fitting the line shape.

3 Transitions

3.1 Hadronic Transitions

In order to conserve charge, transitions can either happen by emitting neutral particles or a charged pion pair. Single π^0 transitions are isospin suppressed. Kaon pair transitions are phase space prohibited.

3.1.1 Non-Dipion transitions

By studying the decay $\psi' \to J/\psi\gamma\gamma$ and plotting the invariant mass of the two photons, evidence for a single pion and η transitions can be obtained. The BES Collaboration, using their 15M ψ' sample, will be able to perform precise measurements of these transitions. To illustrate the quality of the data sample, Figure 3 displays the result of a study of the decay $\psi' \to \gamma\gamma l^+l^-$, where clear π^0 and η signals are observed in the distribution of the invariant $\gamma\gamma$ mass [3].

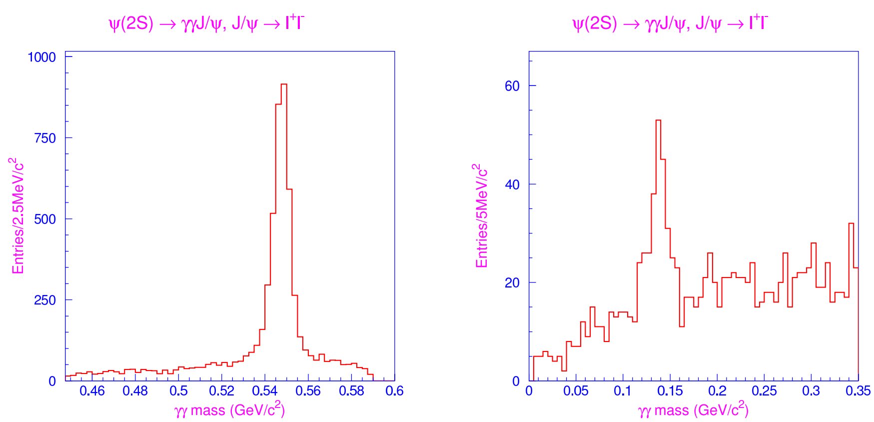

Figure 3: *Evidence for π^0 and η transitions in charmonium [3].*

The first non-pionic hadronic transition in the Υ system was recently found by the CLEO Collaboration. In their sample of $(5.81\pm0.21)\times10^6$ $\Upsilon(3S)$ decays evidence was found for the decay chain $\Upsilon(3S) \to \gamma\chi'_{b1,2} \to \gamma\omega\Upsilon(1S)$ with $\omega \to \pi^+\pi^-\pi^0$

and $\Upsilon(1S) \to l^+l^-$. (The decay $\chi'_{b0} \to \omega\Upsilon(1S)$ is phase space suppressed.) Requiring the presence of an $\Upsilon(1S)$ candidate, identified through its decay into a high-momentum lepton pair, guarantees that the background from *udsc* pair production in the data sample is negligible. The measured branching fractions, obtained by maximum likelihood fit to the energy spectrum of photons not assigned to the π^0 candidates (Figure 4), are at the percent level [4], thereby confirming the prediction that such transitions should have sizeable rates.

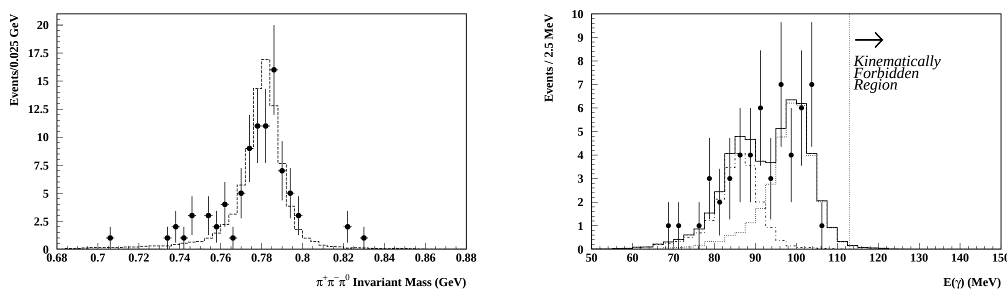

Figure 4: *First observation of a non-pionic hadronic transition in bottomonium: Left: The three pion invariant mass, indicating the presence of an ω. Right: Fit to the photon energy spectrum, with the individual contributions from $\Upsilon(3S) \to \gamma\chi'_{b1}$ (dotted) and $\Upsilon(3S) \to \gamma\chi'_{b2}$ (dash-dotted) overlaid.*

3.1.2 Dipion transitions

When comparing the dipion invariant mass spectrum in $\psi' \to \psi\pi^+\pi^-$, $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$, and $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$, the last has a distinctive double-peak structure (Figure 5, right) [5]. Many models have been developed that try and fit this behaviour, albeit lack of precision did not allow a clear discrimination between the models. CLEO has presented new preliminary data [7]. The structure is confirmed in both $\pi^+\pi^-$ and $\pi^0\pi^0$ reactions, measured exclusively and inclusively, see Figure 5.

4 Charmonium Singlet States

The ground state of charmonium, η_c, has been studied for some time. Theoretical predictions of the mass and width of its first radial excitation have so far been limited to potential model calculations and based on drawing an analogy of the $S = 0$ pair (η'_c, η_c) to the $S = 1$ pair (ψ', J/ψ). An early measurement by Crystal Ball yielded a particularly low η'_c mass, thereby introducing a lower value for the mass

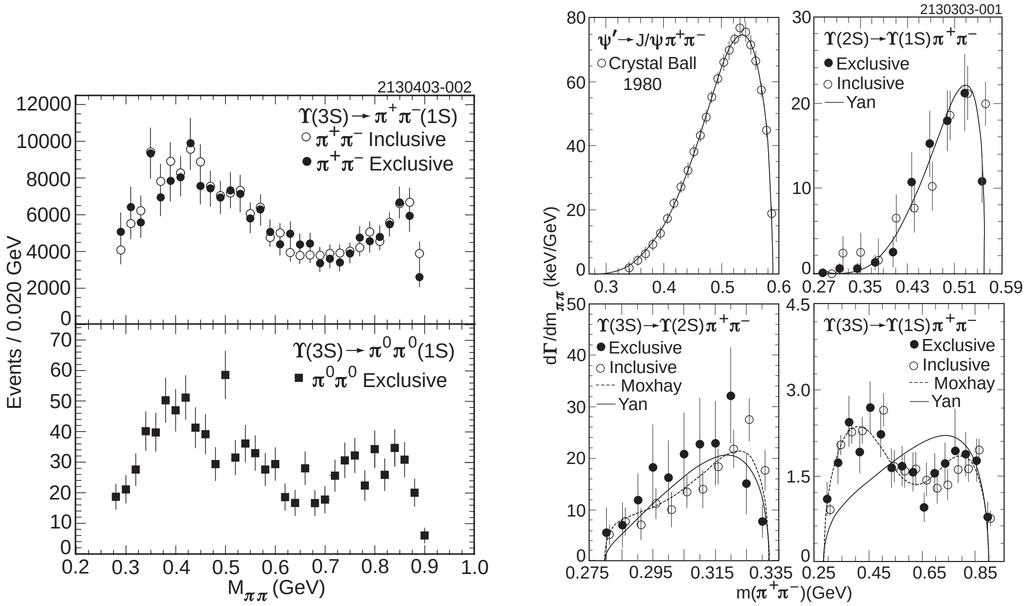

Figure 5: *The dipion invariant mass spectrum in hadronic onia transitions. Left: new preliminary CLEO data, right: previous results from Crystal Ball [6] ($\psi' \to \psi\pi^+\pi^-$) and CLEO [5] ($\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$, and $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$).*

splitting $\Delta m = m(\eta_c') - m(\eta_c)$. Recent measurements of CLEO and BaBar using two photon events and Belle studying $B \to K\eta_c' \to KK_sK^-\pi^+$ decays [8] give ample indication towards a higher value, as does a Belle measurement of the spectrum of the system recoiling against the J/ψ [9] in $e^+e^- \to J/\psi X$. At the same time, the η_c mass has been remeasured in these experiments. A precision measurement was performed by BES using radiative decays in a 58M J/ψ data set [10]. A summary of experimental data on the η_c and η_c' masses can be found in Table 1. Of particular interest to theorists will be the mass splitting between the two $n = 1,\ L = 0$ states, $m(\eta_c') - m(\psi')$, in comparison to the $n = 0$ states, used to calculate the strength of the spin-spin interaction term in non-relativistic potential models.

Many attempts have been made to measure the 1^1P_1 state in charmonium, labeled h_c [15]. So far, the results are suggestive, but not conclusive. In [16], the branching fraction $\mathcal{B}(\psi' \to \pi^0 h_c)$ is predicted to be as large as 3.7×10^{-3}, with $\mathcal{B}(h_c \to \gamma\eta_c)$ as large as 50%. Combined with a reasonable detection efficiency, even a moderate size ψ' data sample should be able to test this prediction.

Table 1: *Experimental η_c and η_c' mass measurements.*

experiment	$m(\eta_c)$ (MeV)	$m(\eta_c')$ (MeV)
Crystal Ball	2980 ± 8 [12]	3594 ± 5 [13]
Belle 2003 (exclusive)	$2979 \pm 2(stat)$	$3654 \pm 6(stat) \pm 8(syst)$
Belle 2003 (recoil)	$2962 \pm 13(stat)$	$3622 \pm 12(stat)$
BaBar 2003 ($\gamma\gamma$)	$2983.3 \pm 1.2(stat) \pm 1.8(syst)$	$3632.2 \pm 5.0(stat) \pm 1.8(syst)$
CLEOII/II.V 2003 ($\gamma\gamma$)	2984.7 ± 2.1	$3642.7 \pm 4.1 \pm 4.0(syst)$
BES 2003 (J/ψ decay)	$2977.5 \pm 1.0(stat) \pm 1.2(syst)$	
Potential models [14]		$3594 - 3629$

5 Search For New States in Bottomonium Using Radiative $\Upsilon(nS)$ decays

In contrast to the situation in charmonium, no singlet $b\bar{b}$ state has been observed yet: the bottomonium ground state 1^1S_0, $\eta_b(1S)$, has not been seen (and neither have its excitations), which is also true for the h_b states, n^1P_1. Since they are not accessible in direct production, they are searched for by making use of photon transitions.

CLEO studied magnetic dipole (M1) transitions from the triplet S states[1], using 4×10^6 $\Upsilon(3S)$ and 3×10^6 $\Upsilon(2S)$ decays. The reactions examined in an inclusive photon spectrum analysis are: $\Upsilon(3S) \to \eta_b(2S)\gamma$, $\Upsilon(3S) \to \eta_b(1S)\gamma$, $\Upsilon(2S) \to \eta_b(1S)\gamma$, and $\Upsilon(3S) \to h_b(1P)\pi\pi$ with $h_b \to \gamma\eta_b$. A search window was defined based on predictions of the hyperfine splitting between the $\eta_b(nS)$ and $\Upsilon(nS)$ states and the h_b and χ_b states. As a preliminary result [7], no signal was found, but upper limits at the 10^{-3} level in the corresponding search windows have been set on the branching fractions. This already rules out some of the models. Also, it states that a significant improvement in data sample size will be needed to establish a signal.

5.1 $L = 2$ in Bottomonium

The $\Upsilon(1D)$, a $L = 2$ state, is unique in that it is the only stable high-L state in heavy quarkonia as all others lie above open production threshold. Providing experimental evicendence is not only a matter of principle, but allows for discrimination amongst various theoretical models that were tuned on $L = 0, 1$ states. A second way in which such a state is special is that it decays preferentially electromagnetically, thereby is comparatively narrow. It was searched for by the CLEO Collaboration

[1]These allow $\Delta L = 0$. Direct transitions have $\Delta n = 0$, whereas the ones with $\Delta n > 0$ are called hindered. Hindered transitions, due to small wave function overlap made possible only by relativistic corrections, are suppressed, but benefit from a E^3 dependence in the transition rate, where E is the energy difference between the states.

in $\Upsilon(3S)$ decays in four-photon cascades: $\Upsilon(3S) \to \gamma\chi_b(2P)$, $\chi_b(2S) \to \gamma\Upsilon(1D)$, $\Upsilon(1D) \to \gamma\chi_b(1P)$, $\chi_b(1P) \to \gamma\Upsilon(1S)$. A signal of 6.8σ significance is seen at 10161.2 ± 1.6 MeV[17], inconsistent with $J = 3$. Theory predicts dominance of the $J = 2$ state over $J = 1$ by a factor of about six [18]. The new state is therefore assigned to be the $\Upsilon(1^3D_2)$.

6 Scans

Precise cross-section determinations around a resonance as function of the center-of-mass energy, often referred to as "scans", are an excellent tool to determine the resonance parameters with as little bias as possible.

6.1 BES ψ' scan

The BES Collaboration has determined ψ' resonance parameters [19], in particular studying the reactions $\psi' \to$ hadrons, $\psi' \to \pi^+\pi^- J/\psi$, and $\psi' \to \mu\mu$. The quantities determined in a simultaneous fit to these cross-sections were Γ_{tot}, Γ_μ, and $\Gamma_{J/\psi\pi^+\pi^-}$, the derived quantities are Γ_{had}, $\mathcal{B}_{had}$, $\mathcal{B}_l$, and $\mathcal{B}_{J/\psi\pi^+\pi^-}$:

- The channel $\psi' \to \mu\mu$ can be combined with other leptonic width measurements, testing the sequential lepton hypothesis, which states that :

$$\frac{B_l}{v_l(\frac{3}{2} - \frac{1}{2}v_l^2)} \text{ with } v_l = \sqrt{1 - 4m_l^2/M_{\psi'}^2}$$

  should be the same number for $l = e, \mu, \tau$. The denominator is about unity for $l = e, \mu$ and 0.39 for $l = \tau$. This BES determination of the muonic branching fraction yielded $\mathcal{B}_\mu = (9.2 \pm 0.8) \times 10^{-3}$. The E760 Collaboration published a value of $\mathcal{B}_e = (8.3 \pm 0.5(stat) \pm 0.7(syst)) \times 10^{-3}$. A separate (and first direct) measurement of $\mathcal{B}_\tau$ was performed as well by the BES collaboration [20], resulting in a value of $\mathcal{B}_\tau = (2.71 \pm 0.43 \pm 0.55) \times 10^{-3}$. After applying the above correction factor to the the τ partial decay width, it can be compared with the other leptonic branching fractions. Agreement within experimental errors is observed.

- The $\psi' \to \pi^+\pi^- J/\psi$ line shape is of importance since this decay is frequently used as a normalizing mode. The precision obtained on the branching fraction in this measurement is 4.4%, improved over the PDG2002 value of 5.2%.

- Finally, using the relations $\Gamma_{tot} = \Gamma_{had} + \Gamma_\mu + \Gamma_e + \Gamma_\tau$ and $\Gamma_e = \Gamma_\mu = \Gamma_\tau/0.39$ and measuring the $\psi' \to$ hadrons cross section, Γ_{tot} was obtained as

$\Gamma^{\psi'}_{tot} = (264 \pm 27)$keV. This can be compared with a PDG2002 value of $\Gamma^{\psi'}_{tot} = (300{\pm}25)$keV [11] and a $p\bar{p}$ scan result by E760 of $\Gamma^{\psi'}_{tot} = (306{\pm}36{\pm}16)$ keV [21].

6.2 CLEO $\Upsilon(1, 2, 3S)$ scans

CLEO hopes to improve the precision of the leptonic width Γ_e from currently 2, 4, 9% for $\Upsilon(1, 2, 3S)$ down to the level of 2% for each of the three. One reason is that this parameter enters many other measurements. In addition, it provides a high-precision test for Lattice QCD, which begins to be able to reach this level of accuracy. Preliminary results show a statistical precision of 0.1, 0.3, 0.5%. Systematic errors are still being evaluated.

7 Decays

Heavy onia can decay via the electromagnetic or the strong force. Possible decay mechanisms for a heavy onium state are annihilation of the two heavy quarks into two leptons, one or more photons, or two or three gluons. For states below open flavour production threshold, the decay into leptons only contributes little to the total width (12% for the J/ψ, less for other states), and the remaining hadronic rate is by far not accounted for by the exlusive decays measured so far. To some, the only pieces of information of interest are the leptonic decay widths, since the rest has to consist of radiative or hadronic decays. How exactly this greater remainder of the total rate is divided up into specific final states is largely governed by fragmentation dynamics. Electromagnetic decays have been discussed in Section 6.1.

7.1 First Evidence of $\chi_{cJ} \to \Lambda\bar{\Lambda}$

BES has reported the observation of $\chi_{cJ} \to \Lambda\bar{\Lambda}$ [23]. Besides this being the first measurement of the branching fraction, this decay is of interest in comparison to $\chi_{cJ} \to p\bar{p}$. It has been shown that the lowest Fock-state expansion of charmonium states ("color singlet model", "CSM") is insufficient to describe P-wave quarkonium decays, both inclusively and exclusively, and that use of the next higher Fock-state ("color octet mechanism", "COM") improves the agreement with experiment. The agreement of COM based prediction with the total measured width of the χ_{c0} as well as that for the partial width of $\chi_{cJ} \to p\bar{p}$, obtained by using a carefully tuned nucleon wave function [22], was encouraging. Generalizing the nucleon wave function to other baryons lead to a prediction for the partial width of $\chi_{cJ} \to \Lambda\bar{\Lambda}$ as being about half of that for $\chi_{cJ} \to p\bar{p}$ [22] for $J = 1, 2$.

Table 2: *Experimental results on $\chi_{cJ} \to \Lambda\bar{\Lambda}$, and comparison with $\chi_{cJ} \to p\bar{p}$.*

	$\mathcal{B}(\chi_{cJ} \to \Lambda\bar{\Lambda})$ in 10^{-4}	$\mathcal{B}(\chi_{cJ} \to p\bar{p})$ in 10^{-4}
$J = 0$	$4.7^{+1.3}_{-1.2} \pm 1.0$	2.2 ± 0.5
$J = 1$	$2.6^{+1.0}_{-0.9} \pm 0.6$	0.7 ± 0.3
$J = 2$	$3.3^{+1.5}_{-1.3} \pm 0.7$	0.7 ± 0.1

The analysis uses a recently collected $15M$ sample of ψ' events, decaying radiatively to the χ_c states. The desired channel is identified through one $\pi^- p$ and one charge conjugated candidate. The distribution of the resulting $\Lambda\bar{\Lambda}$ events is shown in Figure 6, overlaid with the fit result, with the masses of the three χ_c states as fit parameters. As a normalizing channel, $\psi' \to \pi\pi J/\psi$ is used. The branching fractions thus derived are listed in Table 2, together with the result for $\chi_{cJ} \to p\bar{p}$ from [11]. The large experimental errors do not justify ruling out the prediction.

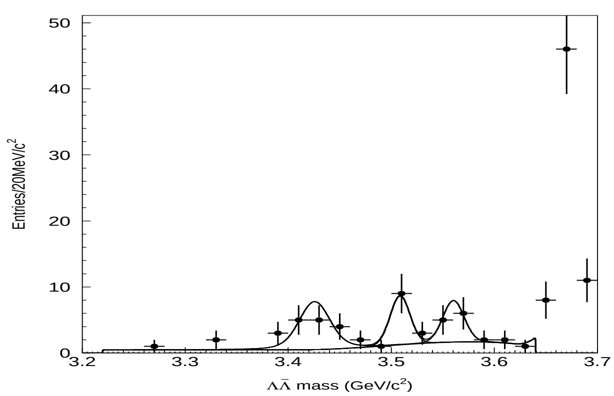

Figure 6: *Distribution of the invariant $\Lambda\bar{\Lambda}$ mass in $\psi' \to \gamma(p\pi^-)(\bar{p}\pi^+)$ events [23].*

7.2 Hadronic Decays

Predictions exist that relate the branching fraction for the 1^3S_1 into hadronic final states to those of its first radial excitation: if this decay happens predominantly via annihilation into gluons, then the wave function overlap should be the only only difference between the decay of the two states (aside from the difference in center-of-mass energy that the gluons have, which is not vastly different). This in turn can be taken from the leptonic branching fraction, another annihilation process. Ignoring the running of the strong coupling constant[2] α_s, one obtains

$$Q = \frac{\mathcal{B}(\psi(2S) \to H)}{\mathcal{B}(J/\psi \to H)} \approx \frac{\mathcal{B}(\psi(2S) \to e^+e^-)}{\mathcal{B}(J/\psi \to e^+e^-)}. \tag{1}$$

Using the leptonic branching fractions $\mathcal{B}(J/\psi \to e^+e^-) = (5.93 \pm 0.1) \times 10^{-2}$ and $\mathcal{B}(\psi(2S) \to e^+e^-) = (7.3 \pm 0.4) \times 10^{-3}$ [11], the expected value for the ratio is $Q = (12.3 \pm 0.9)\%$. Different views exist as to whether this prediction is valid only for the inclusive process $\psi(nS) \to X$ or also for specific final states. Some theorists posit that it should hold also for radiative decays. Moreover, a similar relation should exist for the ratio for the $S = 0$ states.

A number of channels have been studied in charmonium, including decays into a vector (V) and a pseudoscalar (P) particle, axialvector pseudoscalar, vector plus a tensor (T), radiative decays, multibody decays, as well as dibaryon final states [11, 25]. While many of these are not in outrageous disagreement with the above prediction, two VP modes are well-known for failing: $\rho\pi$ ($Q_{\rho\pi} < 0.65\%$) and K^*K ($Q_{K^*K} < 1\%$). Also in VT states substantially lower ratios have been observed ($Q_{\omega f_2} < 3.5\%$, $Q_{\rho a_2} < 2\%$). The overall picture is not clear, in part due to inaccurate experimental results. Many a theorist has given input on this anomaly [26] that is often referred to as the $\rho\pi$ puzzle, but so far none is able to explain all experimental results. It is of major interest to decide whether the J/ψ rate is enhanced or the ψ' rate is suppressed.

In the Υ system, a similar relation is expected to hold. As in this case two excitations are below dissociation threshold, two such ratios can be built. Using the corresponding leptonic branching ratios, one obtains 48% for $\Upsilon(2S) : \Upsilon(1S)$ and 72% for $\Upsilon(3S) : \Upsilon(1S)$. It is by no means clear what absolute rate to expect for Υ decays when extrapolating from charmonium. Depending on the model chosen to explain the $\rho\pi$ anomaly, the rates vary considerably. A preliminary CLEO result studying a variety of two-body hadronic Υ decays are upper limits of $4 \cdot 10^{-5}$ or better on $\rho\pi$, $K^*(892)\bar{K}$, $\rho a_2(1320)$, $K^*(892)\bar{K}_2^*(1430)$, $\omega f_2(1270)$, $b_1(1235)\pi$, and $K_1(1400)\bar{K}$ on the $\Upsilon(1, 2, 3S)$ resonances [27]. In particular, it is found that $\mathcal{B}(\Upsilon(1S) \to \rho\pi)$ is well below 10^{-5}.

8 Summary

Heavy quarkonia continue to provide a testing ground for QCD calculations.

A wide variety of measurements is being carried out, with hopes for many more results once BES and CLEO have analyzed their recently taken large datasets.

[2] A value of 0.85 is quoted for $\left(\alpha_s(m_{\psi(2S)})/\alpha_s(m_{J/\psi})\right)^3$ in [24].

The goals for the future are to establish the states that have been predicted to exist but not observed yet and to provide precision measurement to allow a detailed comparison with theory.

This will hopefully make it possible to gain further insight into the non-perturbative realm of QCD, from which many measurements in other areas will benefit greatly.

9 Acknowledgements

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